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TRANSOM calculations of the flow past SSPA 720

David Hally

Defence R&D Canada

Technical Report

DREA TR 2001-167

May 2002

National Defence Défense nationale

Canada

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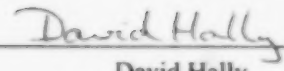

David Hally

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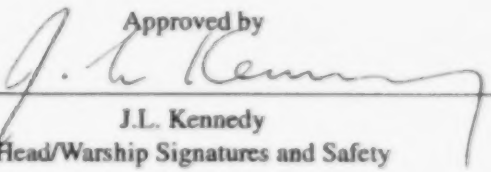

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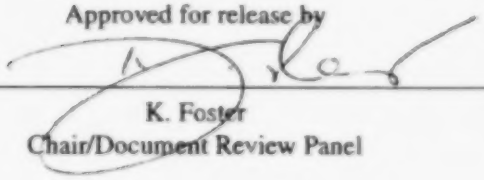

K. Foster
Chair/Document Review Panel

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Abstract

The Reynolds-averaged Navier-Stokes solver TRANSOM, developed at Defence Research Establishment Atlantic (DREA), has been used to calculate the flow around the double hull ship tanker model SSPA 720. The Spalart-Allmaras turbulence model was used. The results have been compared with the hot wire anemometry data of Larsson. Agreement between the calculations and experimental data is very good suggesting that the Spalart-Allmaras model will be sufficient for calculating the flows around many of the hulls of interest to the Department of National Defence.

Résumé

Nous avons utilisé le solutionneur TRANSOM de l'équation de Navier-Stokes moyennée (RANS), mis au point au Centre de recherches pour la défense Atlantique (CRDA), pour calculer l'écoulement autour de la maquette de pétrolier à double coque SSPA 720. Nous avons utilisé le modèle de turbulence de Spalart-Allmaras. Les résultats des calculs ont été comparés aux données d'anémométrie à fil chaud de Larsson. L'accord entre les résultats des calculs et les données expérimentales est très bon, ce qui indique que le modèle de Spalart-Allmaras sera suffisant pour calculer les écoulements autour de plusieurs coques importantes pour le CRDA.

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Executive summary

Introduction

The computer program TRANSOM was developed at DREA to solve a number of flow related problems of importance to the Department of National Defence: for example, flows around submarines, vortex generation from propellers and control surfaces, bilge vortex generation, etc. Of particular interest is the prediction of the flow around a ship and into the propellers. Detailed knowledge of this flow is crucial for the design of efficient, quiet propellers.

TRANSOM is currently being validated by comparing its predictions with a wide variety of flows which have either been measured or for which analytical solutions are known. The current report describes one part of the validation exercise.

Principal results

The flow past the tanker model SSPA 720 was measured in a wind tunnel by L. Larsson in 1974. The flow was measured at 87 different locations on the hull. At each location the fluid velocity was measured at 15 to 45 points on a line normal to the hull. The flow past SSPA 720 has been calculated using TRANSOM and the results compared with Larsson's data at all 87 locations. The agreement with the data is very good at all locations.

Significance of the results

It has been found by other researchers that accurate predictions of the the flow around hulls with high block coefficients requires sophisticated anisotropic turbulence models. In the calculations reported here, a simple isotropic turbulence model, the Spalart-Allmaras model, was used. While SSPA 720 is not the most demanding hull from the point of view of flow predictions, it is not dissimilar in complexity from that of a frigate (though it has a considerably different form). Therefore these results are a strong indication that TRANSOM, when used with the Spalart-Allmaras model, will provide an accurate prediction of the flow around a frigate.

Future work

The validation of TRANSOM will continue using as many different sets of reliable experimental data as possible.

David Hally; 2002; TRANSOM calculations of the flow past SSPA 720; DREA TR 2001-167; Defence Research Establishment Atlantic.

Sommaire

Introduction

Le logiciel TRANSOM a été créé au CRDA pour résoudre certains problèmes d'écoulement importants pour le ministère de la Défense nationale, par exemple : l'écoulement autour des sous-marins et la production de tourbillons par les hélices, les gouvernes ou le bouchain. La prédiction de l'écoulement autour du bateau et vers les hélices est d'un intérêt particulier. Il est crucial de comprendre en détail cet écoulement pour concevoir des hélices efficaces et silencieuses.

Nous testons actuellement la validité du logiciel TRANSOM en comparant ses prédictions avec divers écoulements déjà mesurés ou pour lesquels existe une solution analytique. Le présent rapport ne décrit qu'une partie du travail de validation.

Résultats principaux

En 1974, L. Larsson a mesuré en soufflerie l'écoulement le long de la maquette de pétrolier SSPA 720, et, ce, à 87 positions le long de la coque. Pour chacune des positions, il a mesuré la vitesse d'écoulement pour 15 à 45 points le long de la ligne normale au profil de la coque. Nous avons calculé avec le logiciel TRANSOM l'écoulement le long de la maquette SSPA 720 et comparé les résultats avec les données de Larsson pour les 87 positions. À toutes les positions, l'accord entre les calculs et les données était très bon.

Importance des résultats

D'autres chercheurs ont déjà constaté que des prédictions précises de l'écoulement autour de coques ayant un coefficient de finesse élevé exigent des modèles sophistiqués de turbulence anisotrope. Nous avons utilisé pour les calculs présentés ici, le modèle de Spalart-Allmaras, un modèle simple de turbulence isotrope. Dans une perspective de prédiction de l'écoulement, la coque de la maquette SSPA 720 n'est certes pas la plus exigeante ; toutefois, sur le plan de la complexité, elle ne diffère pas beaucoup de la coque d'une frégate (bien que sa forme soit très différente). Ces résultats nous indiquent donc clairement que le logiciel TRANSOM avec le modèle de turbulence de Spalart-Allmaras donnera des prédictions exactes de l'écoulement autour d'une frégate.

Travaux à venir

Nous poursuivrons nos travaux pour valider le logiciel TRANSOM avec le plus grand nombre possible d'ensembles de résultats expérimentaux fiables.

David Hally; 2002; TRANSOM calculations of the flow past SSPA 720; DREA TR 2001-167; Centre de Recherches pour la Défense Atlantique.

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1 Introduction

The computer program TRANSOM[1,2,3] was developed at DREA to solve a number of flow related problems of importance to the Department of National Defence: for example, flows around submarines, vortex generation from propellers and control surfaces, bilge vortex generation, etc. Of particular interest is the prediction of the flow around a ship and into the propellers. Detailed knowledge of this flow is crucial for the design of efficient quiet propellers.

TRANSOM is currently being validated by comparing its predictions with a wide variety of flows which have either been measured or for which analytical solutions are known. The current report describes one part of the validation exercise.

The flow past the tanker model SSPA 720 (see Fig. 1) was measured by Larsson[4] in 1974. The data were later used in a workshop on calculating the flow past ships in 1980[5]. To remove any effects of the free surface, a double hull model was used. The model was placed in a wind tunnel and hot wire anemometry was used to measure velocity profiles at 87 locations on the hull. At each location the fluid velocity was measured at 15 to 45 points normal to the hull such that the full boundary layer was traversed.

The flow past SSPA 720 has been calculated using TRANSOM and the results compared with Larsson's data. Secs. 2–4 describe how the computations were performed. Sec. 5 then compares the results with Larsson's data. The agreement between the calculations and the experiments is discussed in Sec. 6.

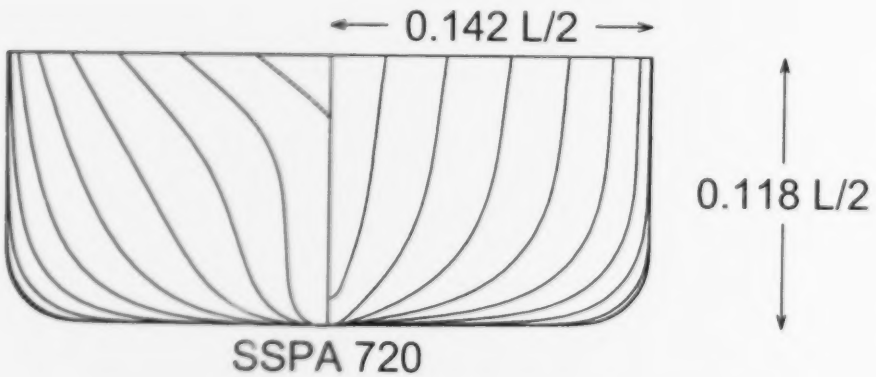

Figure 1: *Offset diagram for SSPA 720: L is the ship length.*

2 The computational grid

A seven block grid was generated for the hull placed within the wind tunnel used in the experiments. Its topology is illustrated in Fig. 2. Symmetry in the centreplane was assumed, so the blocks cover only one half of the tunnel.

The wind tunnel was modelled as a rectangular block extending one ship length upstream and downstream. In practice the tunnel corners were angled, but the difference should have no discernible effect on the flow near the hull.

There are two blocks extending from the bow to the stern. The first joins the lower portion of the hull to the bottom of the tunnel; the second joins the upper portion of the hull to the side of the tunnel.

Similarly there are two blocks upstream, but as the bow is a singular point, each of these blocks has a degenerate face where the centreplane and waterplane meet.

There is a single block which extends from the transom to the downstream boundary. This block has a degenerate face where the centreplane and waterplane meet.

There are two additional blocks in the downstream section: one joins the bottom of the tunnel to the portion of the centreplane below the transom and behind the hull; the second joins the outer face of the transom block to the side of the tunnel.

A total of 632043 nodes was used with 71 nodes along the length of the hull, 55 from keel to waterline, and 71 from the hull to the tunnel walls. The nodes were clustered near the hull so that the nearest nodes had y^+ values of about 1. The points were not clustered near the tunnel walls.

To improve the quality of the grid, Thomas-Middlecoff[6] elliptic smoothing was used for the points on the hull and for the points in the upstream and downstream faces.

3 Boundary conditions

The Spalart-Allmaras[7] turbulence model was used in the calculations; therefore boundary conditions for pressure, velocity and the Spalart-Allmaras viscosity were required.

The TRANSOM freestream boundary condition was used on both upstream and downstream boundaries. Points on the hull surface used a solid boundary condition. Points on the side and bottom of the tunnel used a TRANSOM 'specify' boundary condition with the downstream velocity component, V_x, set to 1.0, and the horizontal and vertical velocity components, V_y and V_z, set to zero. Points on the centreplane used a 'specify' boundary condition with V_y and the derivatives of

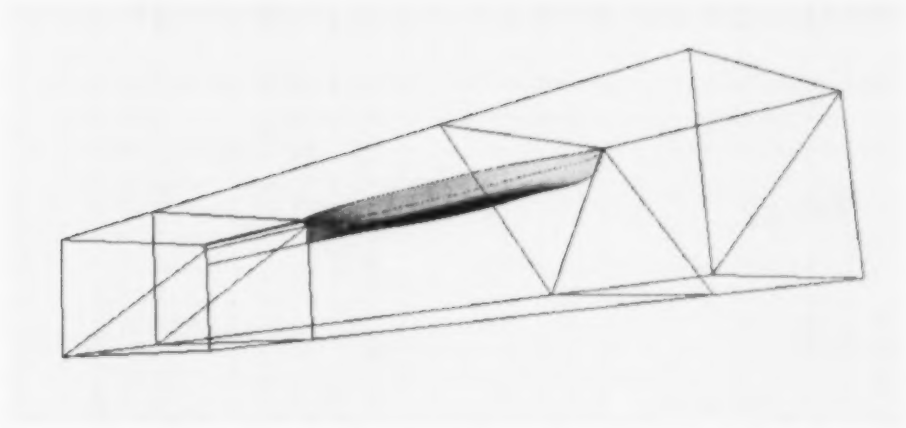

Figure 2: *The grid topology*

V_x, V_z and the Spalart-Allmaras viscosity all set to zero. The boundary condition on the waterplane was similar but V_z and the derivative of V_y were set to zero.

4 Computational strategy

TRANSOM includes two versions of the Spalart-Allmaras turbulence model: one based on a weak conservation formulation of the transport equation and one based on a strong conservation formulation. The former is more robust but does not properly account for cross-derivatives nor for discontinuous metrics at block interfaces. The strong conservation version is fully general but often causes convergence problems within the first few iterations of the solver.

The flow was first calculated using the weak conservation version of the Spalart-Allmaras turbulence model. The metrics in this case were calculated as if they were continuous across block interfaces.

The Spalart-Allmaras viscosity field generated by the weak conservation model was then used to initialize the strong conservation version of the Spalart-Allmaras turbulence model. Discontinuous metrics across block interfaces were accounted for correctly.

During the TRANSOM calculations, a large linear system is constructed and solved. The right hand side vector of the the linear system is called the residual. The linear system matrix is an approximation to the derivatives of the residual with respect to the independent variables (velocity and pressure). Because discontinuous block interfaces decrease the accuracy of the left hand side matrix as an approximation of the derivatives of the residual, it decreases the robustness of the convergence.

Since the convergence rate was poor using the calculated left hand side matrix, a matrix-free linear system[8] was used with ILU0 preconditioning (the highest level of preconditioning available without increasing memory requirements: see Ref. 9 for a description of ILU0 preconditioning). Convergence was then satisfactory with the main trouble spot being at the bottom of the transom where the two hull blocks and the three downstream blocks meet.

5 Comparison of TRANSOM calculations with measurements

At each of the 87 hull locations at which Larsson took data, the TRANSOM data was interpolated onto a series of points normal to the hull. The resulting profiles are compared with the measurements in Figs. A.1–A.87 in Annex A. The locations were organized by Larsson into points on eight streamlines shown in Fig. 3. Streamline 1 is the keel. The higher the streamline number, the closer the streamline is to the waterline.

Larsson tabulated each velocity datum as a velocity magnitude and an angle with the potential flow velocity vector at that point. The component of the velocity normal to the hull was not measured. Moreover, he did not tabulate the values of the potential flow velocity which he used to calculate the flow angles. Therefore, except for the points on Streamline 1, the magnitude of the velocity is known but its direction is not; however, the relative directions of the velocities within each profile are known. For the purpose of comparison, both the experimental and calculated velocities have been resolved into streamwise and cross-stream components as follows.

Let $\mathbf{V}$ be a velocity vector calculated by TRANSOM on a given profile, let $\mathbf{V}_o$ be the velocity vector calculated by TRANSOM at the outermost point on the profile, and let $\hat{\mathbf{n}}$ be a unit normal to the hull for the profile. Define unit vectors $\hat{\mathbf{n}}_s = \mathbf{V}_o/|\mathbf{V}_o|$ and $\hat{\mathbf{n}}_c = \hat{\mathbf{n}} \times \hat{\mathbf{n}}_s$. The TRANSOM velocities were resolved into streamwise and cross-stream components according to:

$$V_s = \mathbf{V} \cdot \hat{\mathbf{n}}_s; \qquad V_c = \mathbf{V} \cdot \hat{\mathbf{n}}_c; \tag{1}$$

The cross-stream velocity, V_c, is positive when it is directed from the waterline toward the keel.

Let (V, β) be a velocity datum on one of Larsson's profiles, where V is the velocity magnitude and β is the angle between the velocity and the potential flow velocity vector for that profile. Then the streamwise and cross-stream components of the velocity are:

$$V_s = V\cos(\beta - \beta_o); \qquad V_c = V\sin(\beta - \beta_o) \tag{2}$$

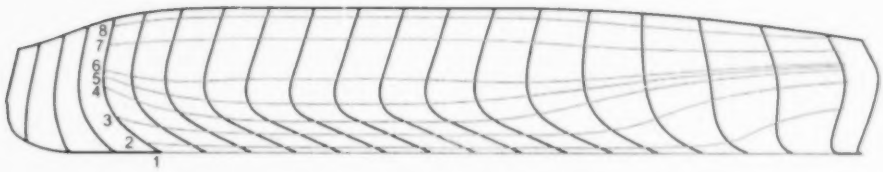

Figure 3: *The eight streamlines*

where β_o is an angular offset equal to the difference in angle between Larsson's calculated potential flow velocity and the measured velocity at the outer points on the profile. Since the calculated potential flow velocity is not known, β_o was chosen so that the root mean square difference between the calculated and measured cross flow velocity was minimized (with the exception of the points on Streamline 1). Because the flow angles are small (typically only a few degrees) the effect of the choice of β_o on the streamwise profile is very small. On Streamline 1, the true velocity is known to lie in the centreplane; therefore β_o was set to zero.

Figs. 4–7 compare calculated contours of the downstream velocity component with measured values at hull stations 16, 17, 18 and 19 (DREA station numbering is from zero at the forward perpendicular to 20 at the aft perpendicular).

6 Discussion of results

In general, the agreement between the calculations and the measured data is very good. In indication of the level of systematic error in the experiments can be obtained from Fig. A.54. During the traverse of this profile the measuring apparatus had to be realigned resulting in a discontinuity in the measured values. The corresponding systematic error in this profile is about 2%. Similarly, the measured crossflow on the keel (Streamline 1: Figs. A.1–A.12) gives an estimate of the errors in the crossflow since these values should be zero. The errors near the bow and stern are roughly 2 to 3% but are considerably smaller near mid-ships. Although the agreement in some figures seems poor, especially for the crossflow, when the size of these experimental errors are considered, the agreement is good.

Because it generates weak bilge vortices, SSPA 720 is not as difficult a test case as tankers with higher block coefficients (e.g. the HSVA tanker or KRISO VLCC2) for which it is appears necessary to use Reynolds stress models for the turbulence to get good agreement with experiment (see, for example, Refs. 10 and 11). Nevertheless, its flow is of similar complexity to that of a typical warship. Therefore these results suggest that the Spalart-Allmaras turbulence model should be adequate for predicting the propeller inflow on most ships of interest to the Canadian Forces.

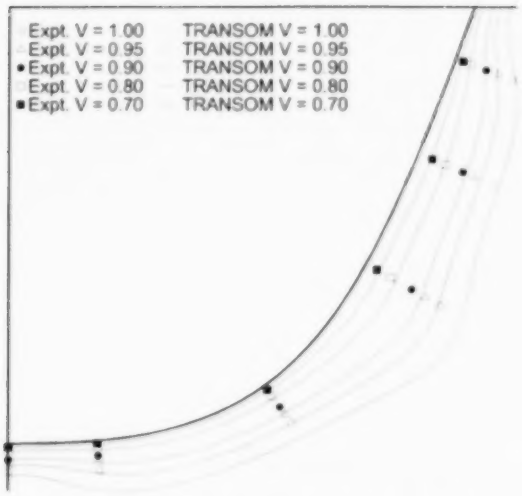

***Figure 4**: Contours of velocity magnitude at Station 16*

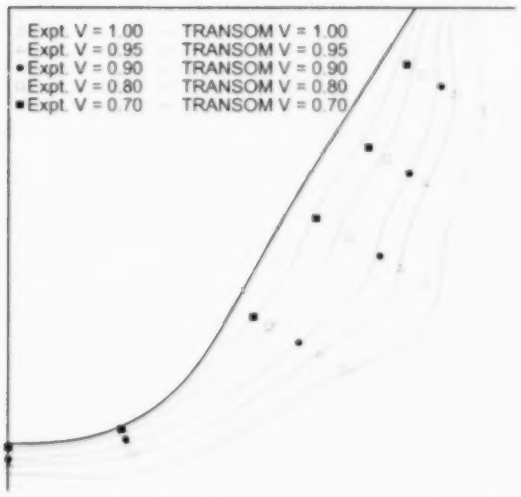

***Figure 5**: Contours of velocity magnitude at Station 17*

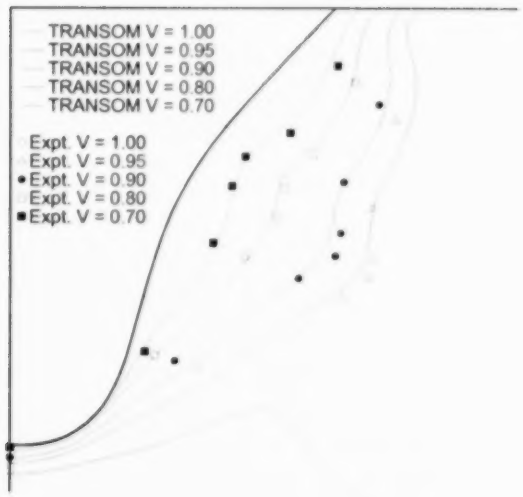

Figure 6: *Contours of velocity magnitude at Station 18*

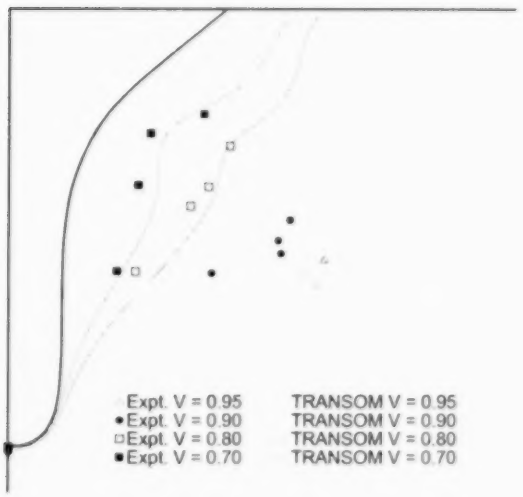

Figure 7: *Contours of velocity magnitude at Station 19*

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Annex A
Comparison of measured and calculated velocity profiles

The figures on the following pages display the velocity profiles at every hull position for which Larsson took measurements. The velocity is decomposed into a streamwise component parallel to the flow at the outer edge of the boundary, and a cross stream component. No normal component was measured.

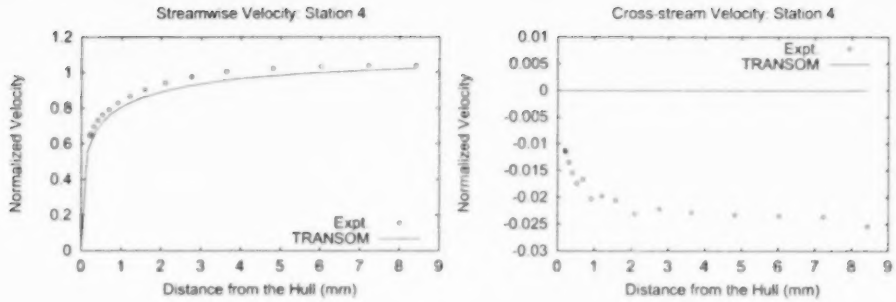


Figure A.1: *Velocity profiles on Station 4, Streamline 1*

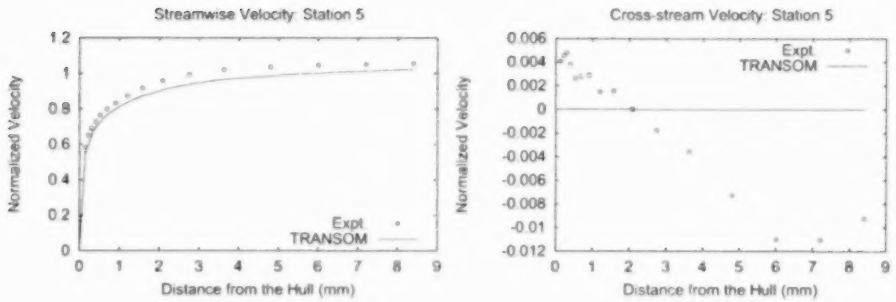


Figure A.2: *Velocity profiles on Station 5, Streamline 1*

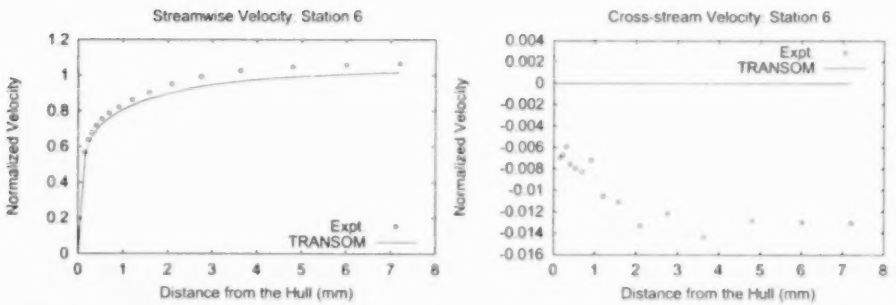


Figure A.3: *Velocity profiles on Station 6, Streamline 1*

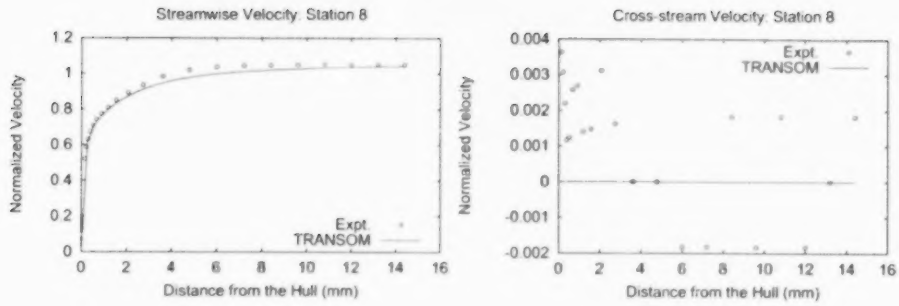


Figure A.4: *Velocity profiles on Station 8, Streamline 1*

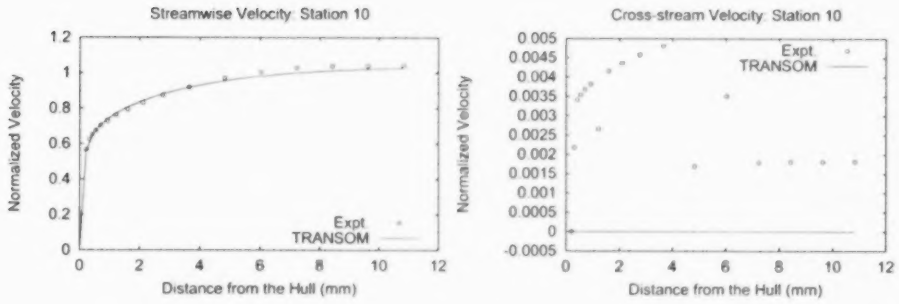


Figure A.5: *Velocity profiles on Station 10, Streamline 1*

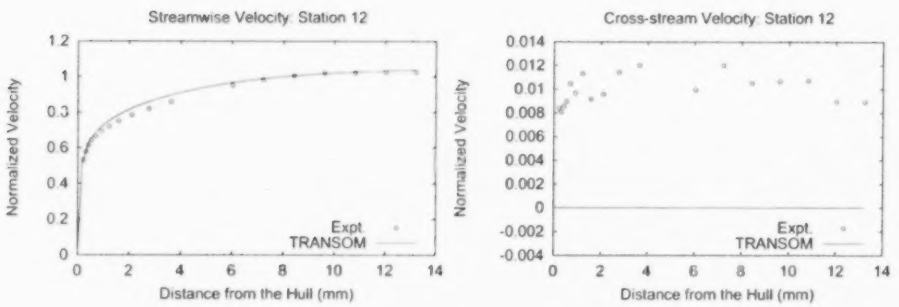


Figure A.6: *Velocity profiles on Station 12, Streamline 1*

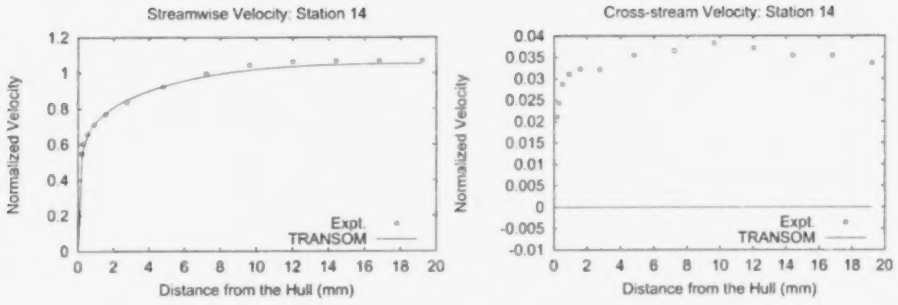


Figure A.7: *Velocity profiles on Station 14, Streamline 1*

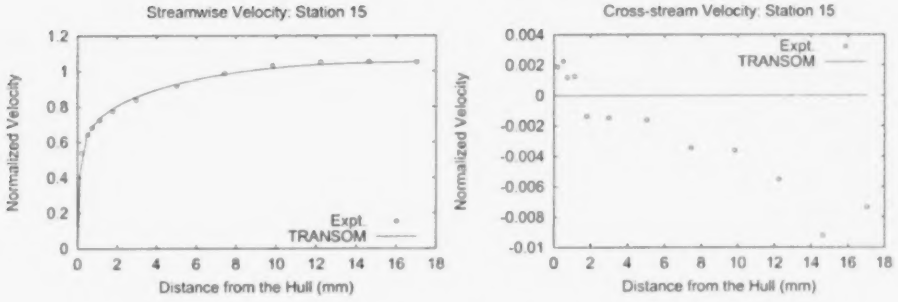


Figure A.8: *Velocity profiles on Station 15, Streamline 1*

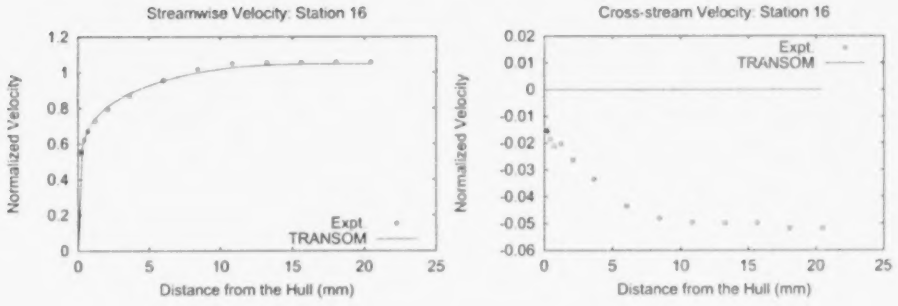


Figure A.9: *Velocity profiles on Station 16, Streamline 1*

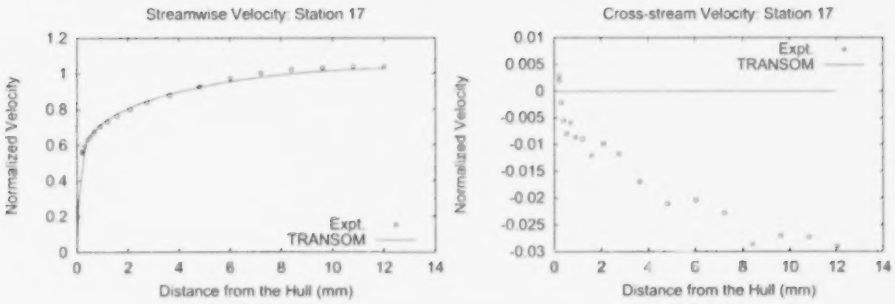


Figure A.10: *Velocity profiles on Station 17, Streamline 1*

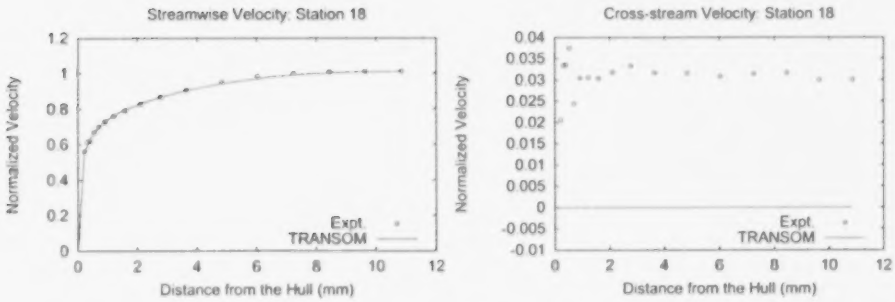


Figure A.11: *Velocity profiles on Station 18, Streamline 1*

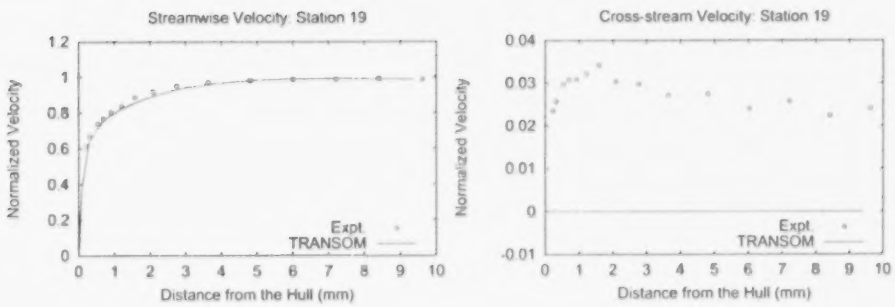


Figure A.12: *Velocity profiles on Station 19, Streamline 1*

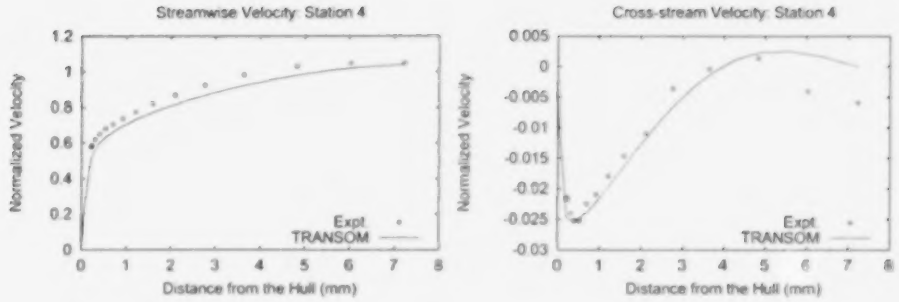


Figure A.13: *Velocity profiles on Station 4, Streamline 2*

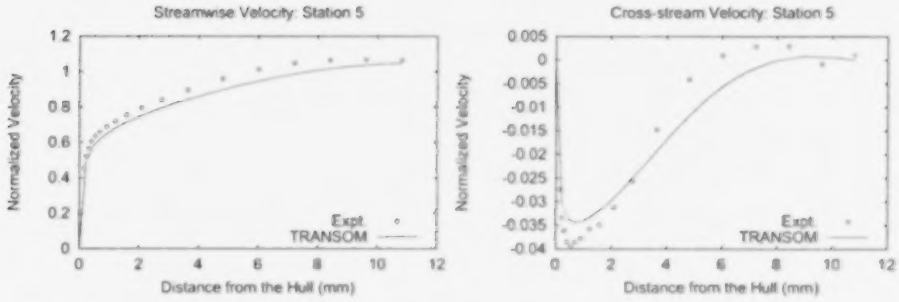


Figure A.14: *Velocity profiles on Station 5, Streamline 2*

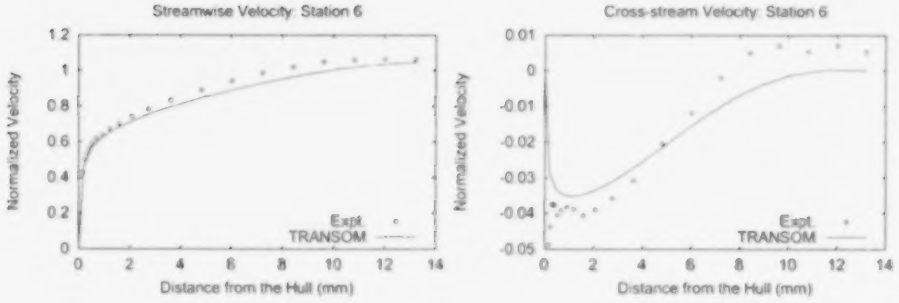


Figure A.15: *Velocity profiles on Station 6, Streamline 2*

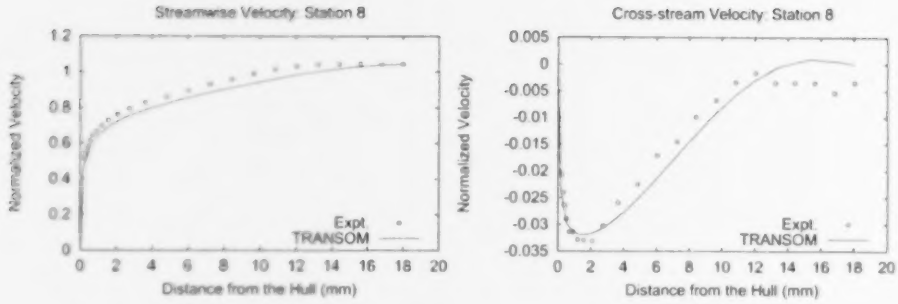


Figure A.16: *Velocity profiles on Station 8, Streamline 2*

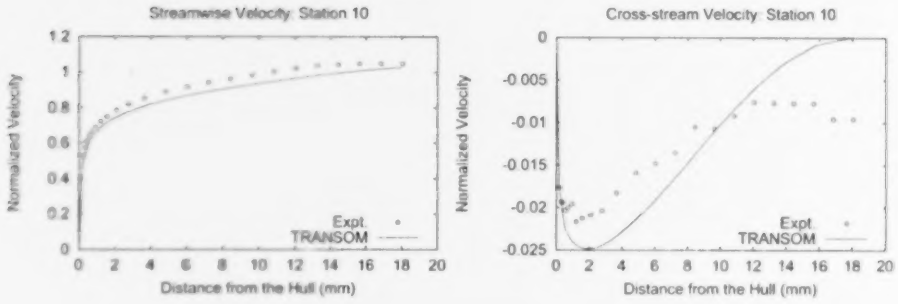


Figure A.17: *Velocity profiles on Station 10, Streamline 2*

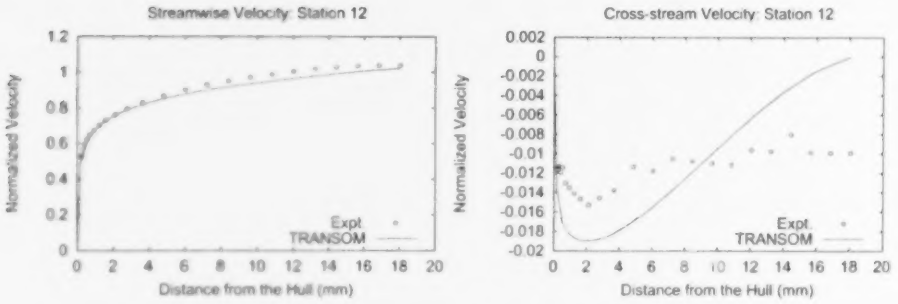


Figure A.18: *Velocity profiles on Station 12, Streamline 2*

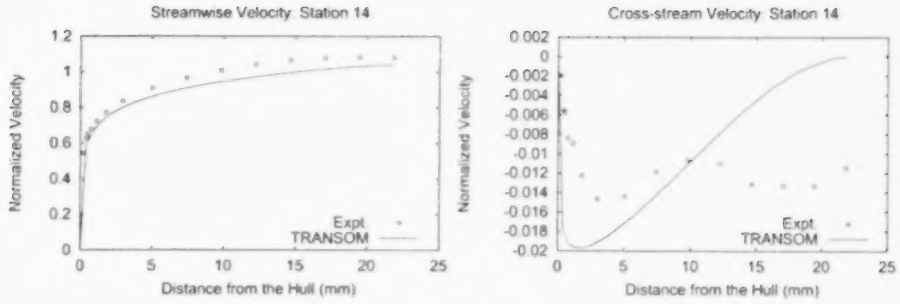


Figure A.19: *Velocity profiles on Station 14, Streamline 2*

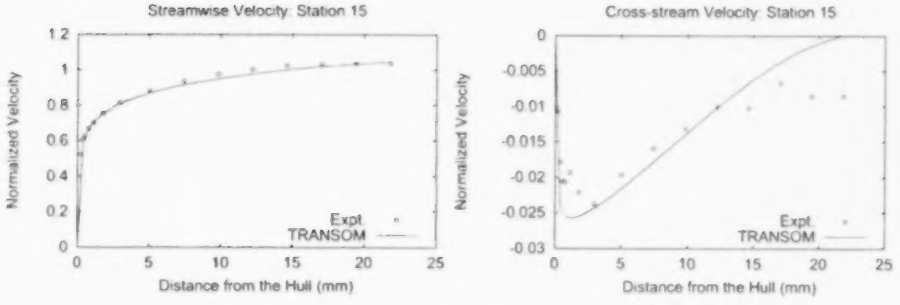


Figure A.20: *Velocity profiles on Station 15, Streamline 2*

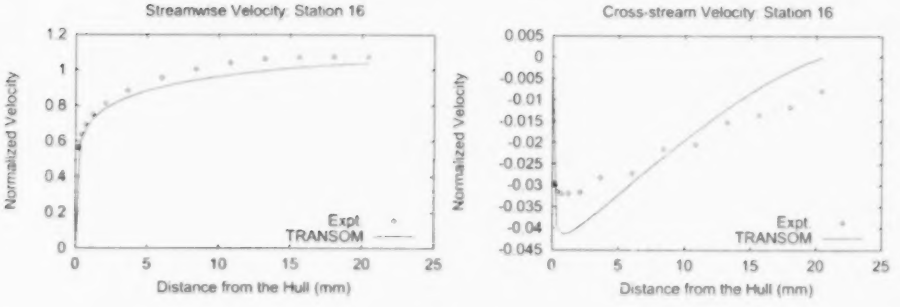


Figure A.21: *Velocity profiles on Station 16, Streamline 2*

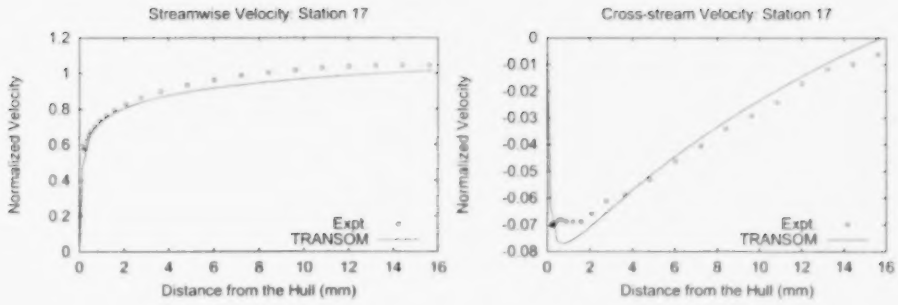


Figure A.22: *Velocity profiles on Station 17, Streamline 2*

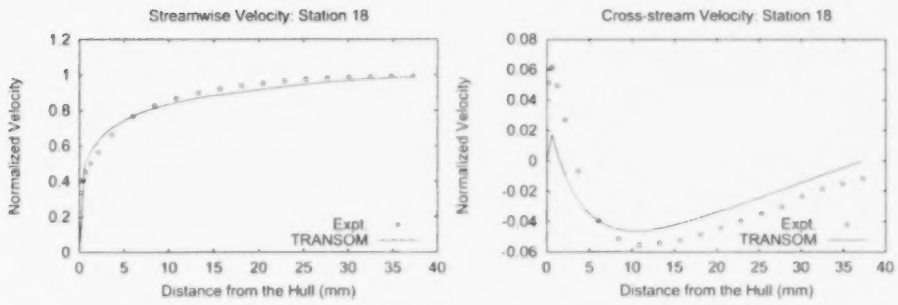


Figure A.23: *Velocity profiles on Station 18, Streamline 2*

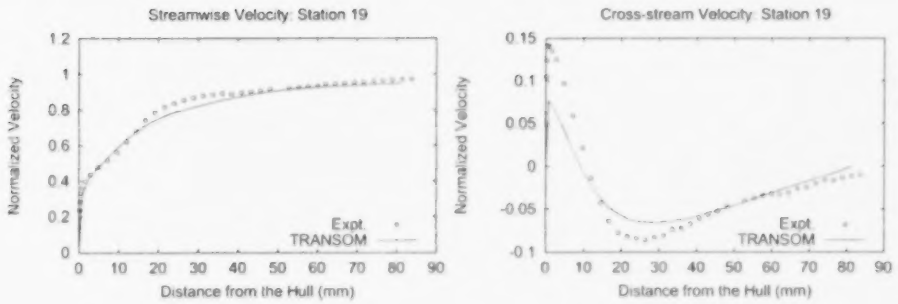


Figure A.24: *Velocity profiles on Station 19, Streamline 2*

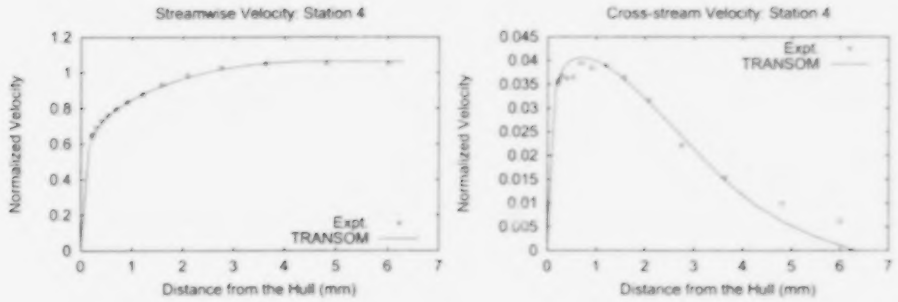


***Figure A.25**: Velocity profiles on Station 4, Streamline 3*

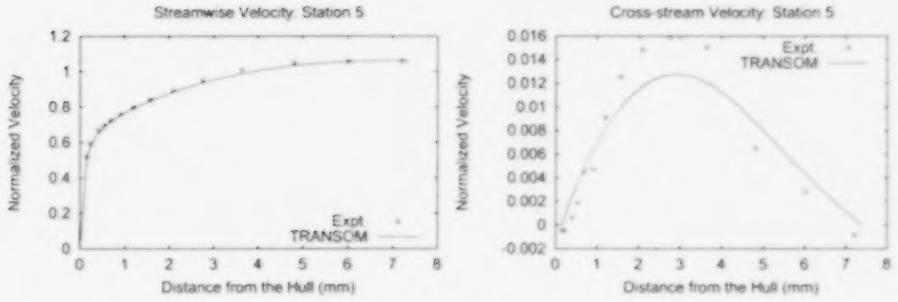


***Figure A.26**: Velocity profiles on Station 5, Streamline 3*

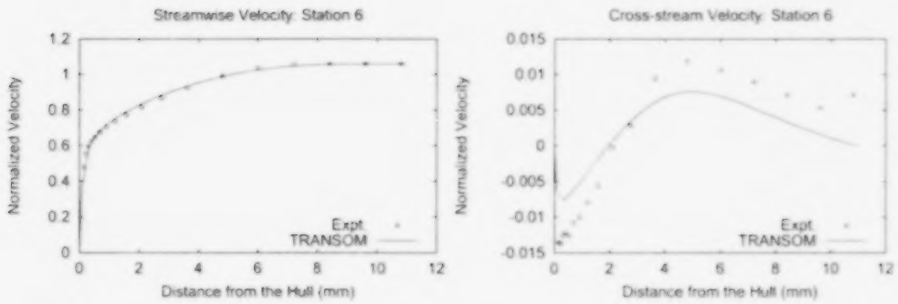


***Figure A.27**: Velocity profiles on Station 6, Streamline 3*

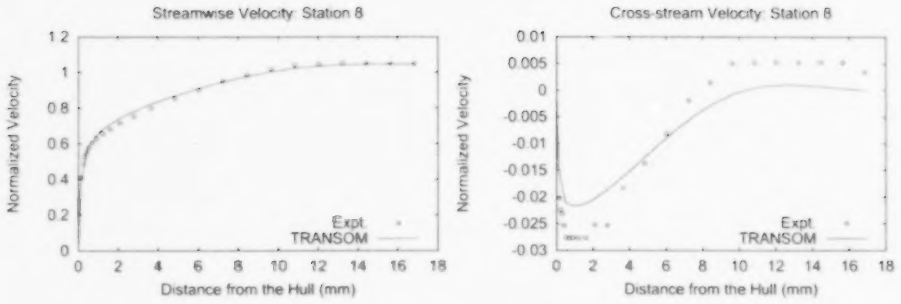


***Figure A.28**: Velocity profiles on Station 8, Streamline 3*

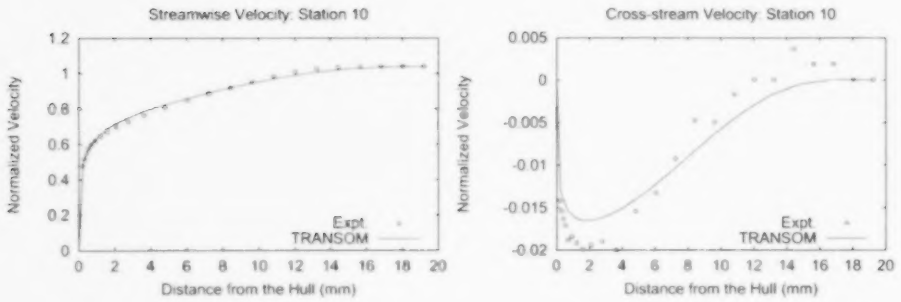


***Figure A.29**: Velocity profiles on Station 10, Streamline 3*

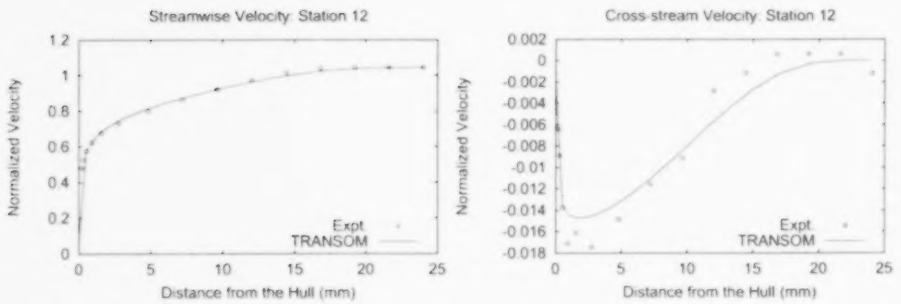


***Figure A.30**: Velocity profiles on Station 12, Streamline 3*

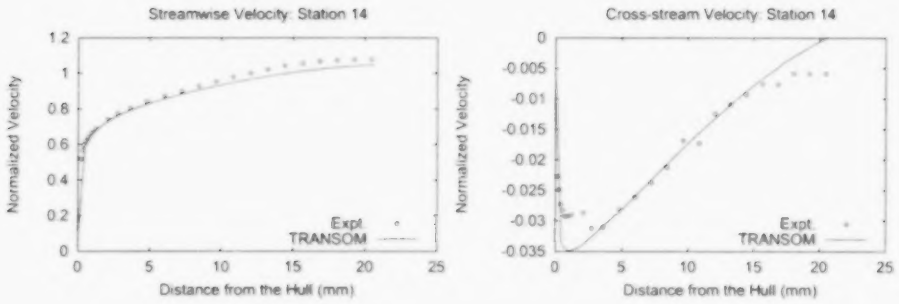


Figure A.31: *Velocity profiles on Station 14, Streamline 3*

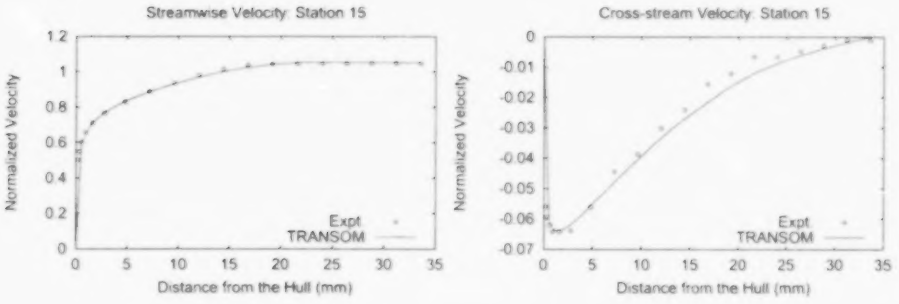


Figure A.32: *Velocity profiles on Station 15, Streamline 3*

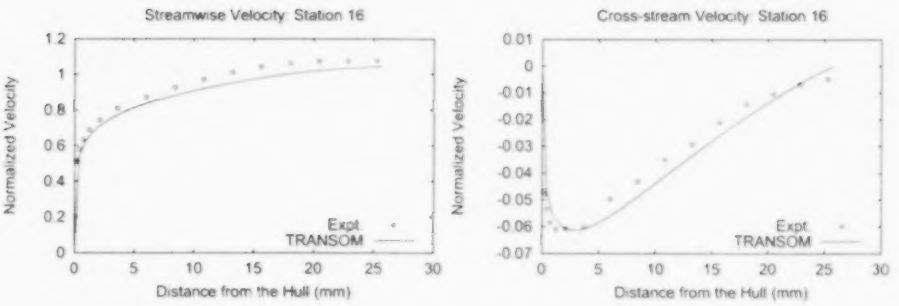


Figure A.33: *Velocity profiles on Station 16, Streamline 3*

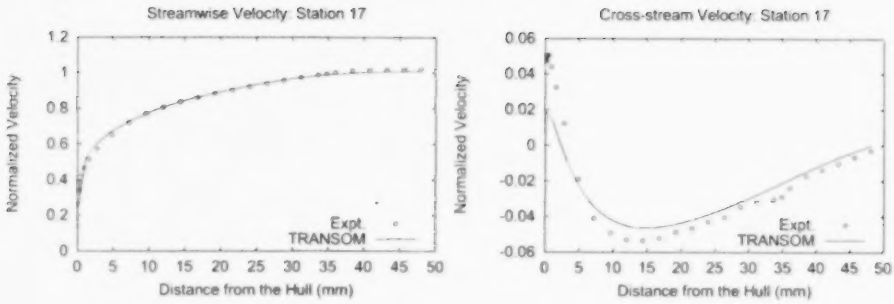


Figure A.34: *Velocity profiles on Station 17, Streamline 3*

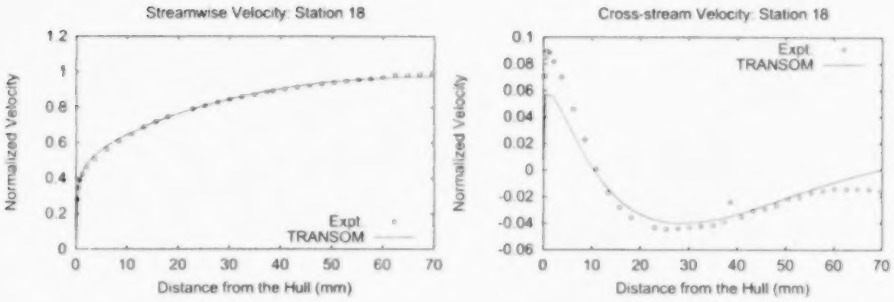


Figure A.35: *Velocity profiles on Station 18, Streamline 3*

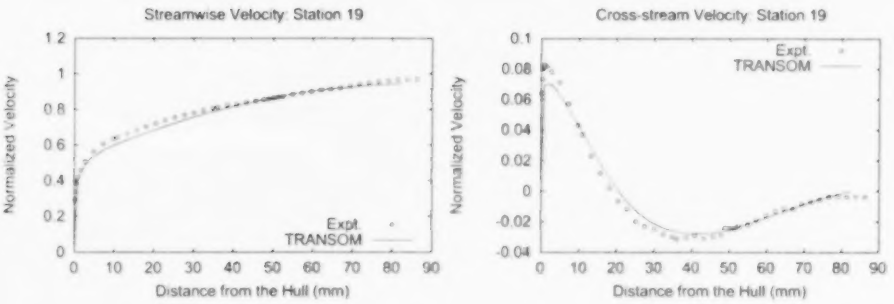


Figure A.36: *Velocity profiles on Station 19, Streamline 3*

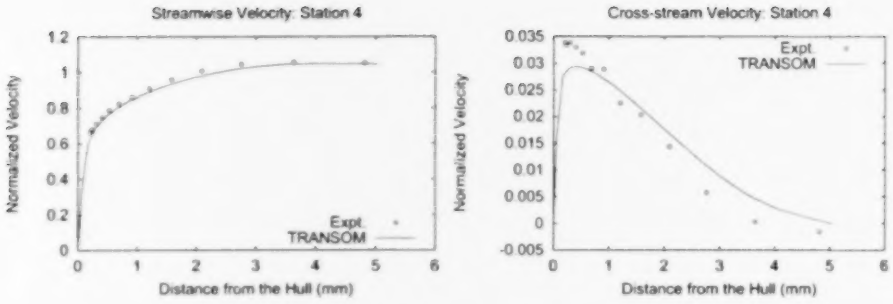


Figure A.37: *Velocity profiles on Station 4, Streamline 4*

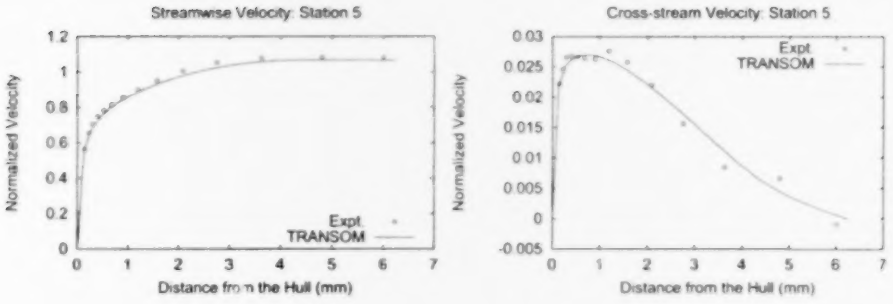


Figure A.38: *Velocity profiles on Station 5, Streamline 4*

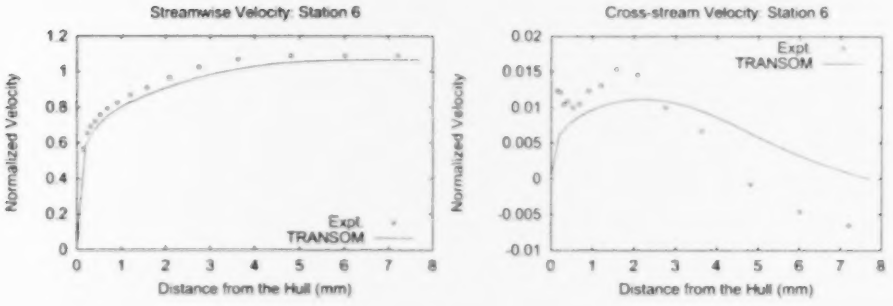


Figure A.39: *Velocity profiles on Station 6, Streamline 4*

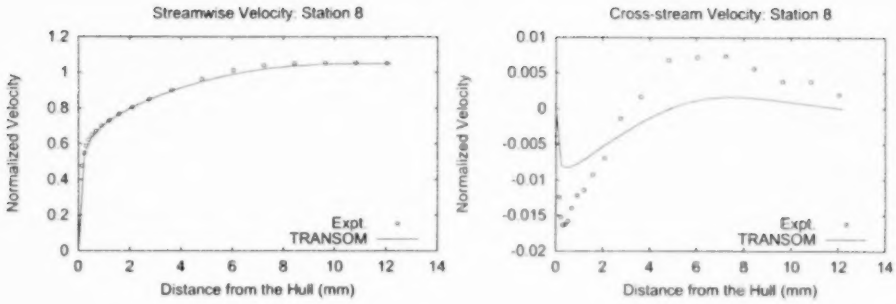


Figure A.40: *Velocity profiles on Station 8, Streamline 4*

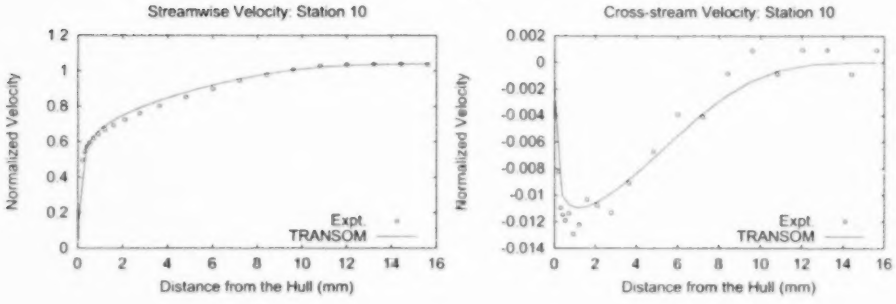


Figure A.41: *Velocity profiles on Station 10, Streamline 4*

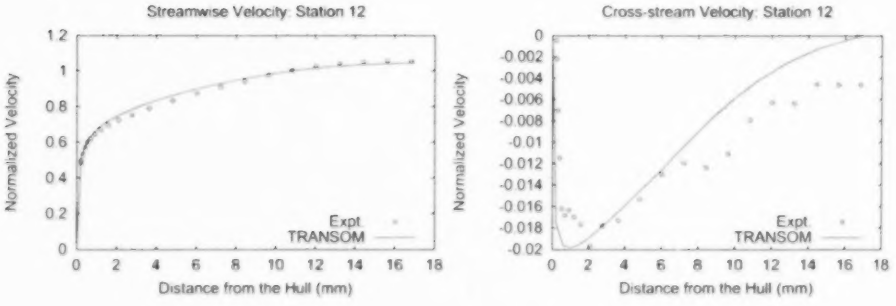


Figure A.42: *Velocity profiles on Station 12, Streamline 4*

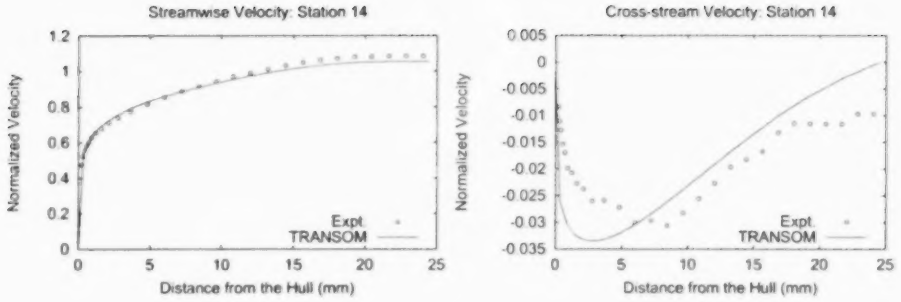


Figure A.43: *Velocity profiles on Station 14, Streamline 4*

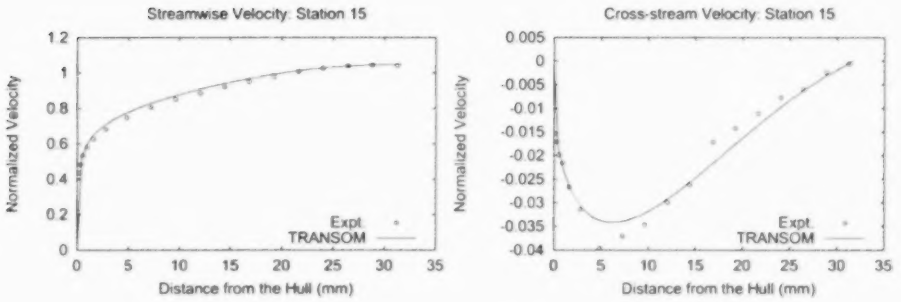


Figure A.44: *Velocity profiles on Station 15, Streamline 4*

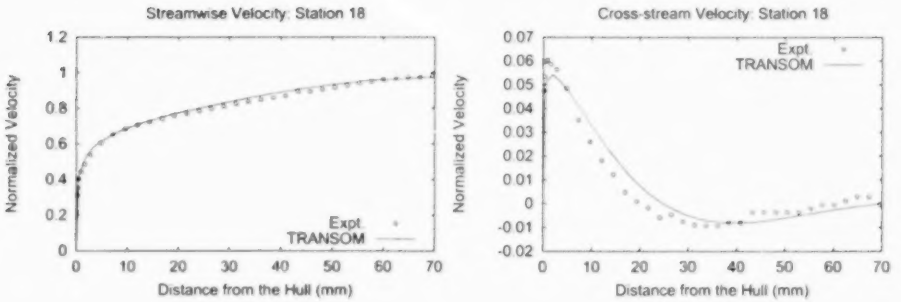


Figure A.45: *Velocity profiles on Station 18, Streamline 4*

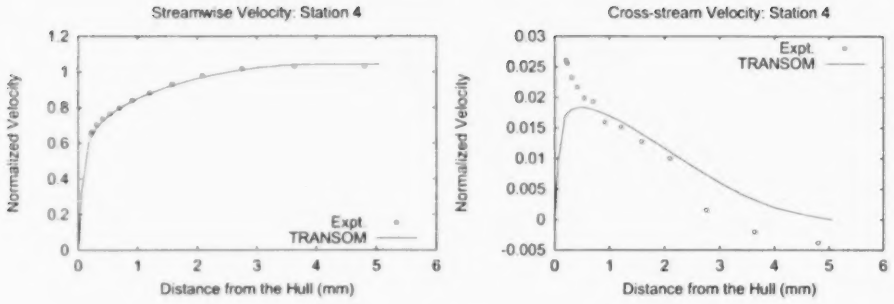


Figure A.46: *Velocity profiles on Station 4, Streamline 5*

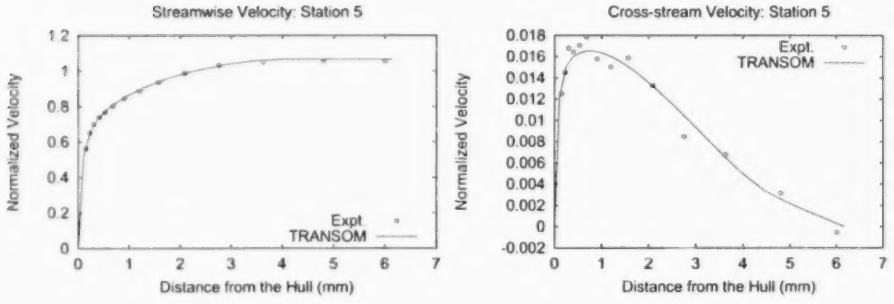


Figure A.47: *Velocity profiles on Station 5, Streamline 5*

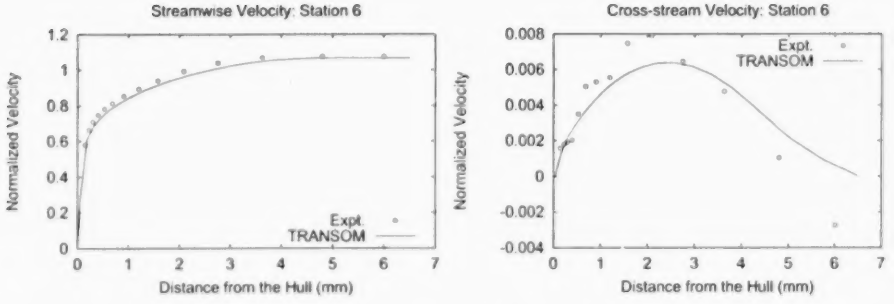


Figure A.48: *Velocity profiles on Station 6, Streamline 5*

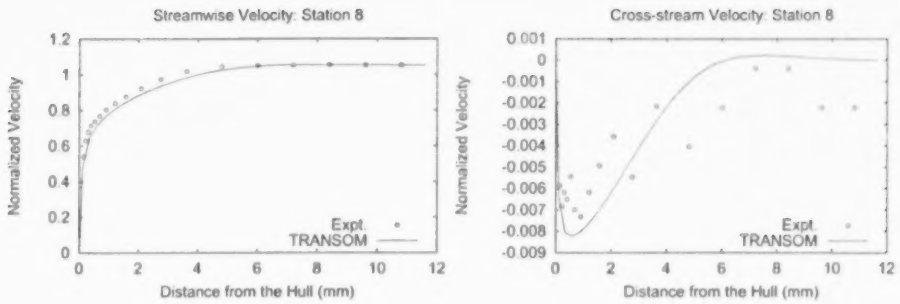


Figure A.49: *Velocity profiles on Station 8, Streamline 5*

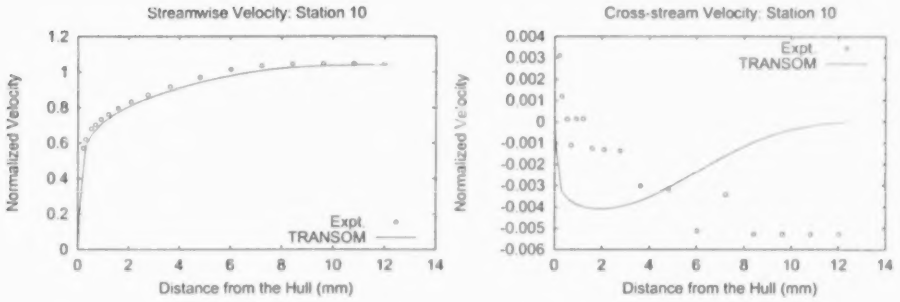
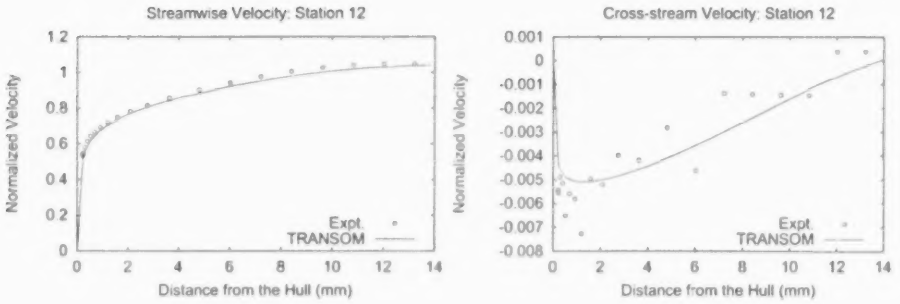


Figure A.50: *Velocity profiles on Station 10, Streamline 5*



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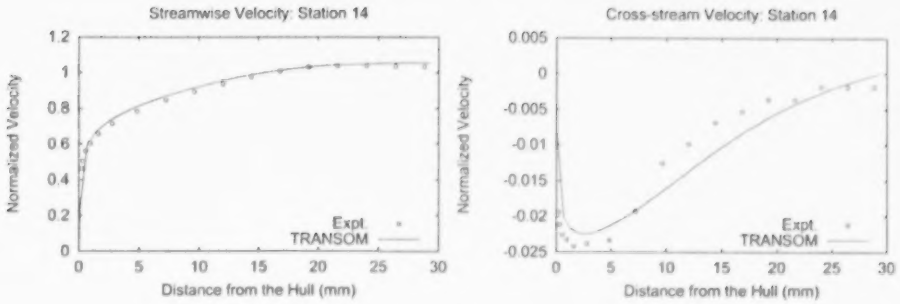

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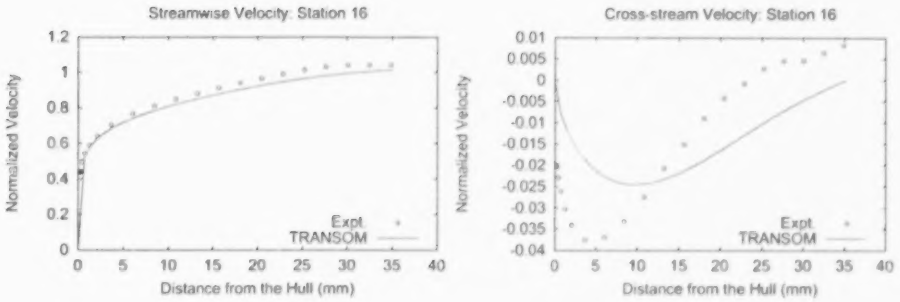

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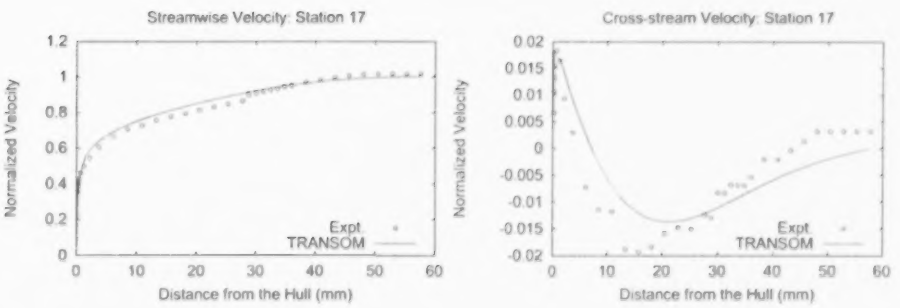

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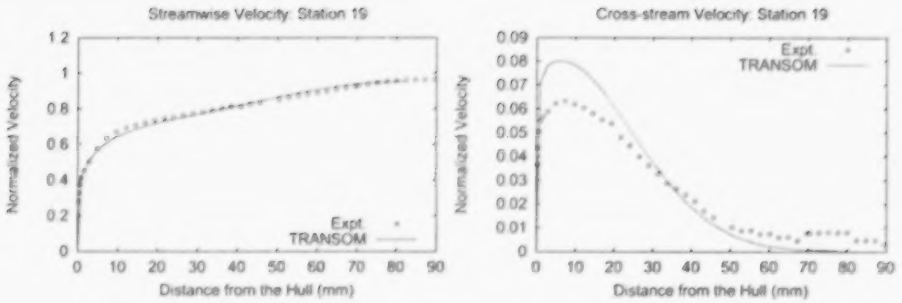

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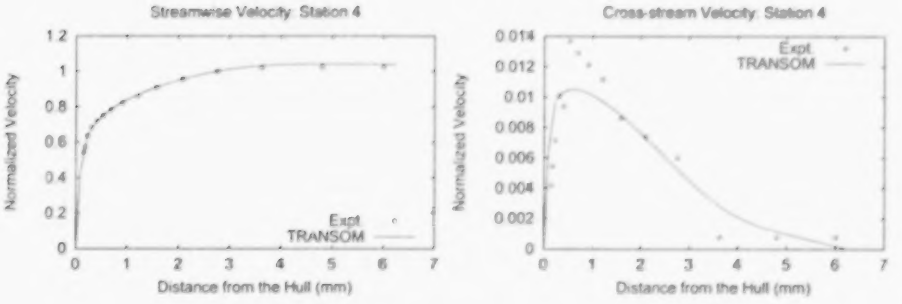

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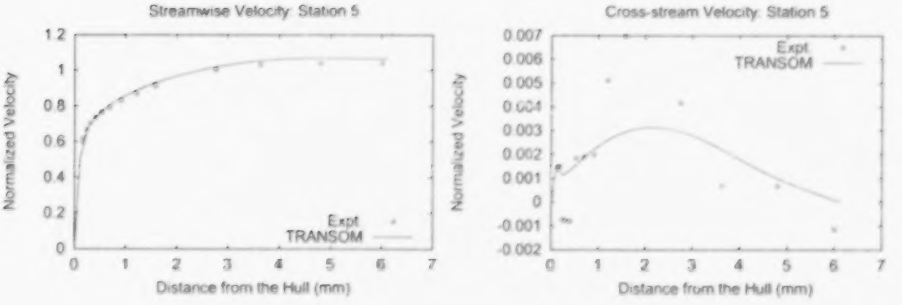

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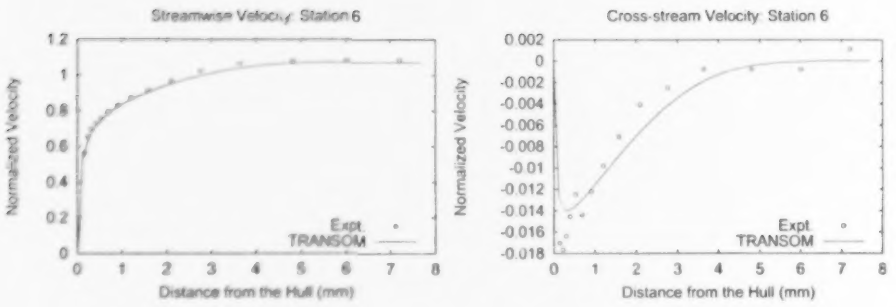

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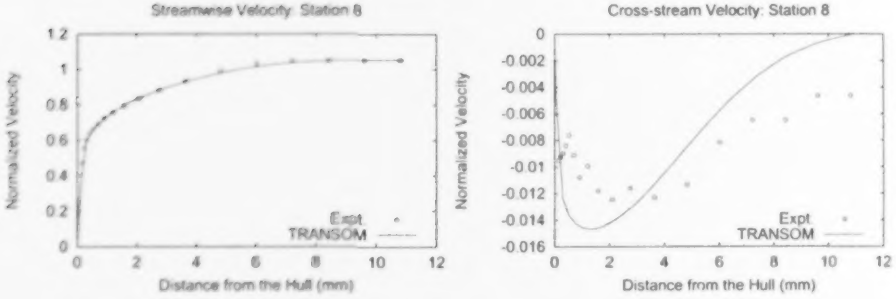

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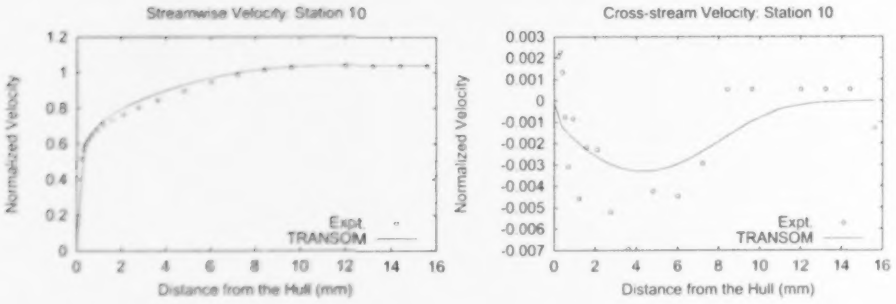

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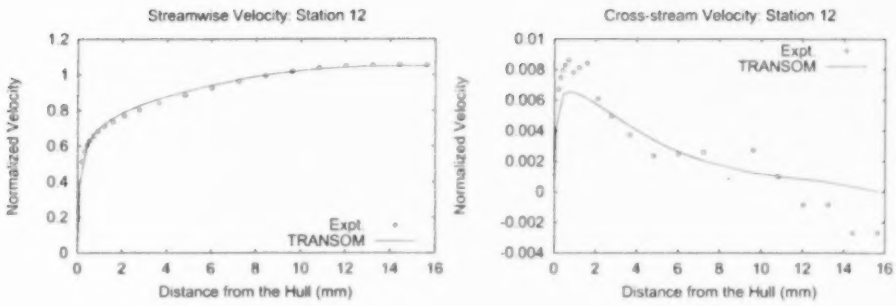

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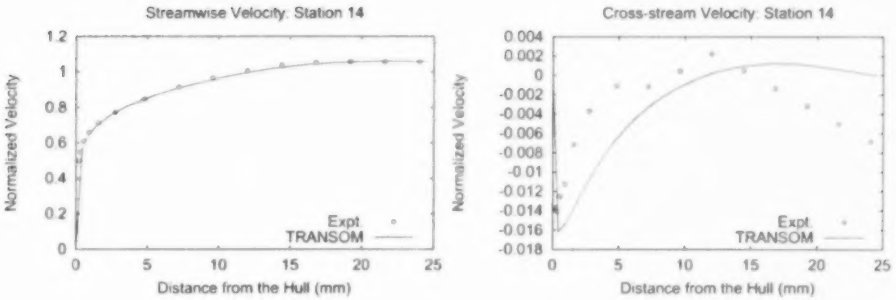

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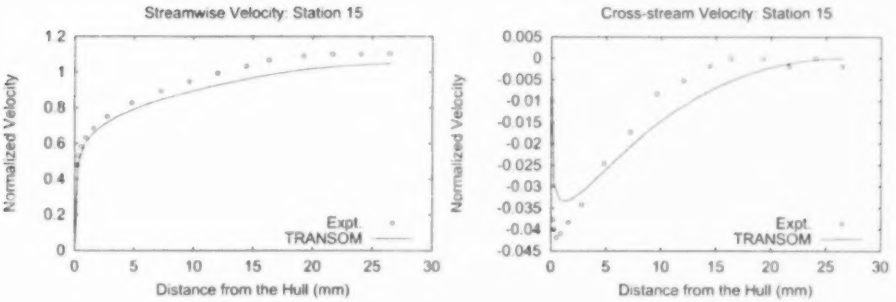

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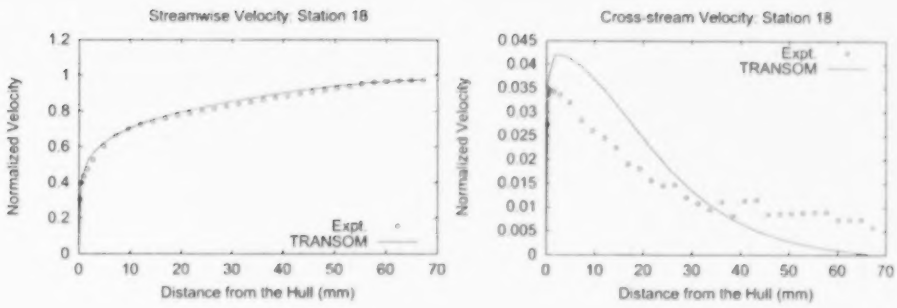

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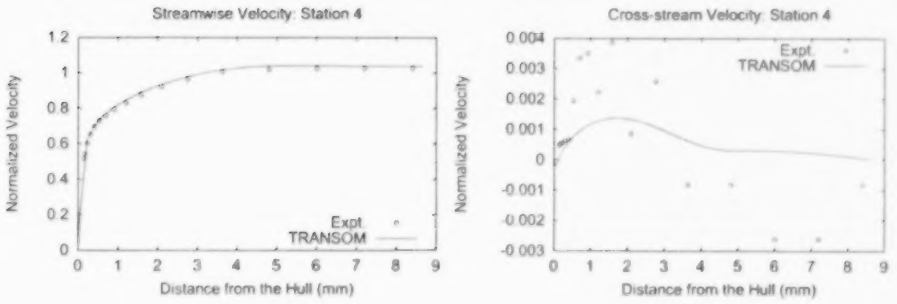

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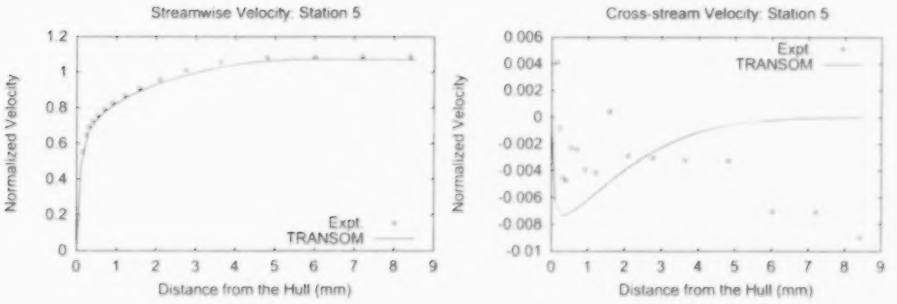

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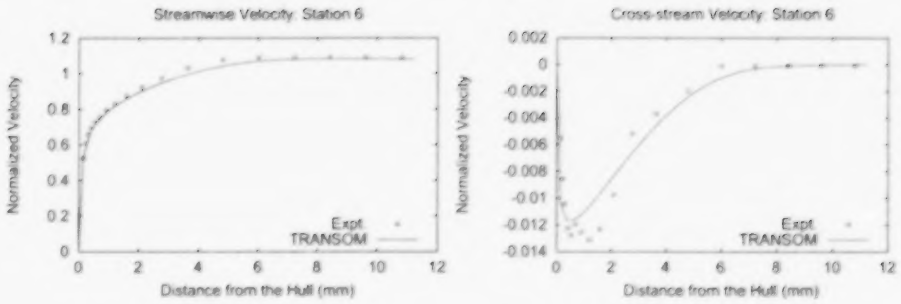

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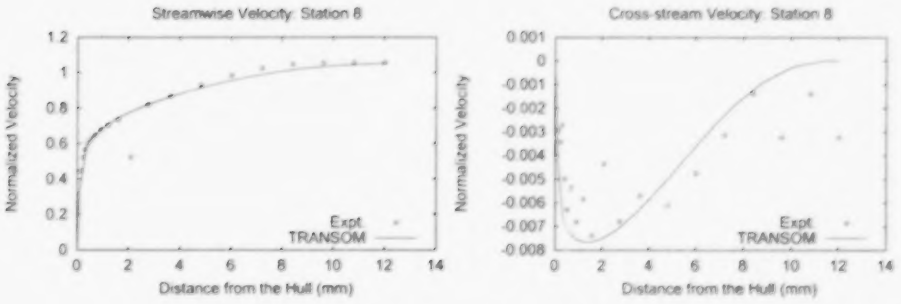

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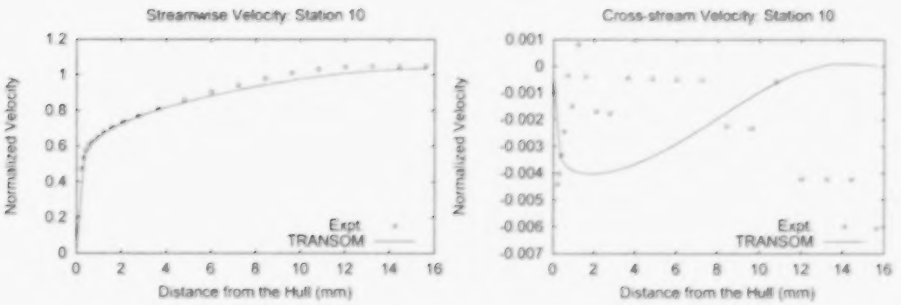

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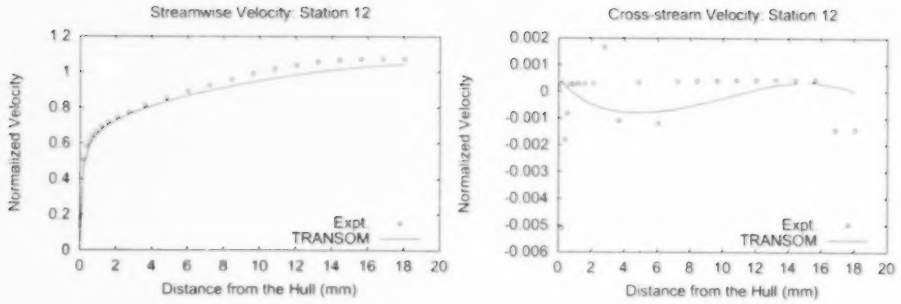

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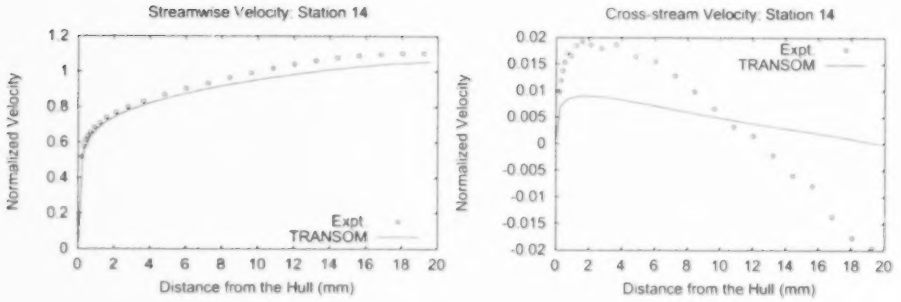

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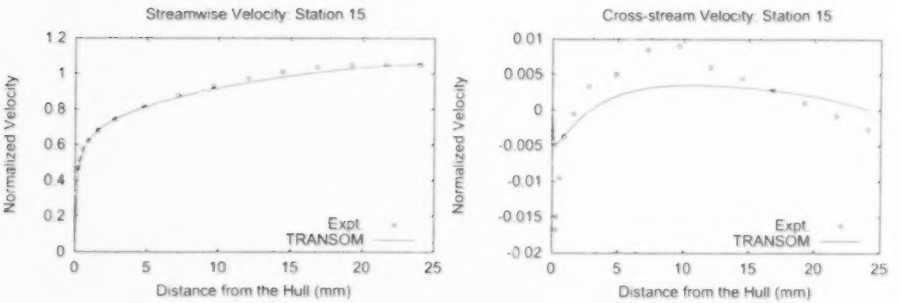

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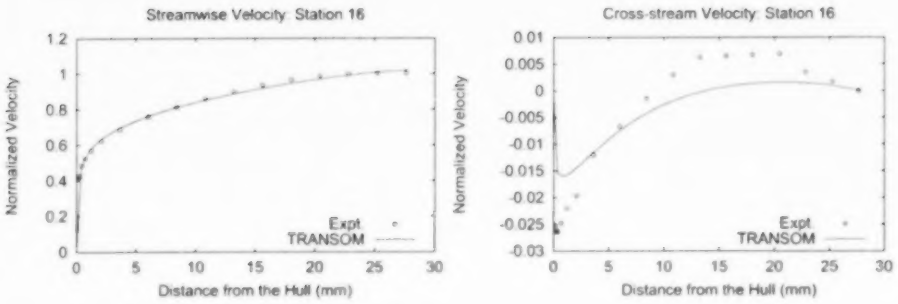

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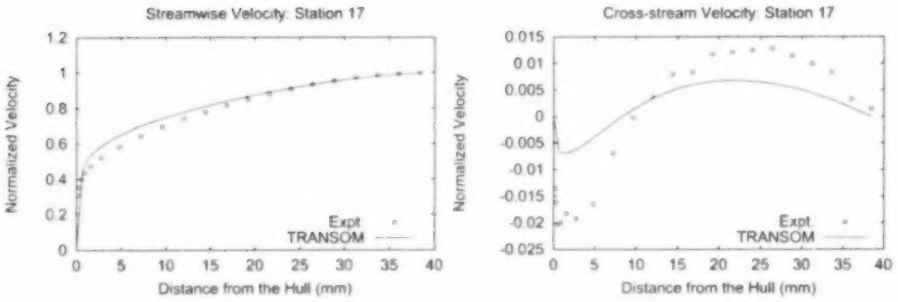

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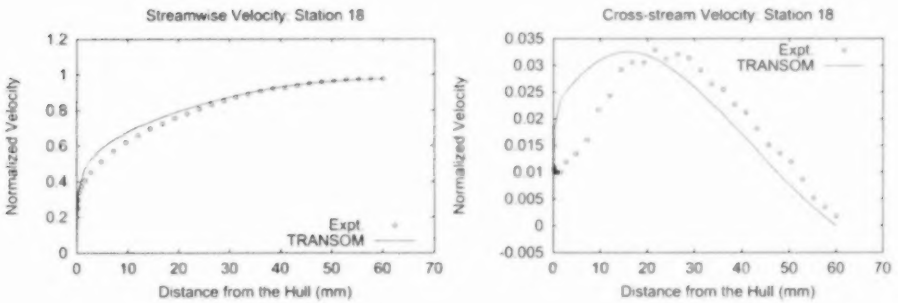

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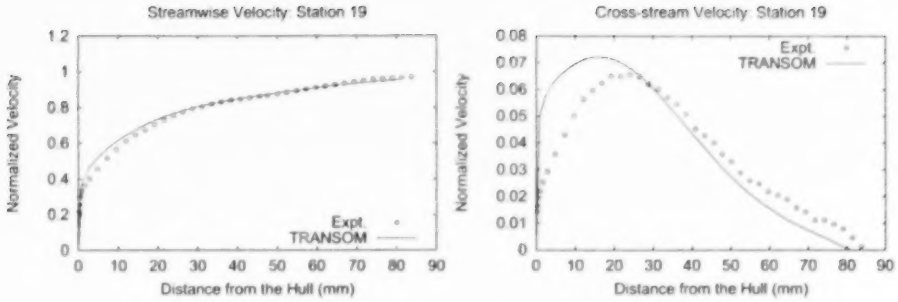

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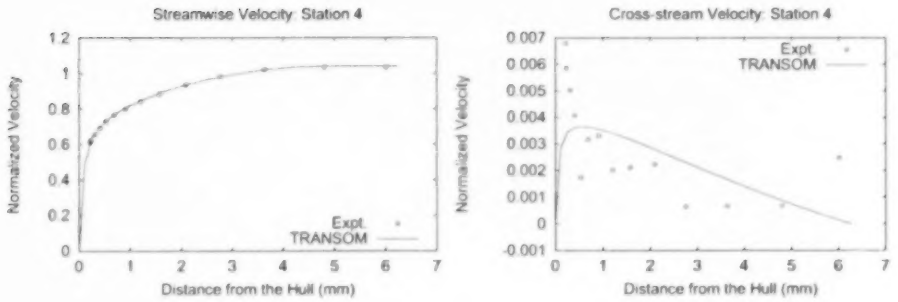

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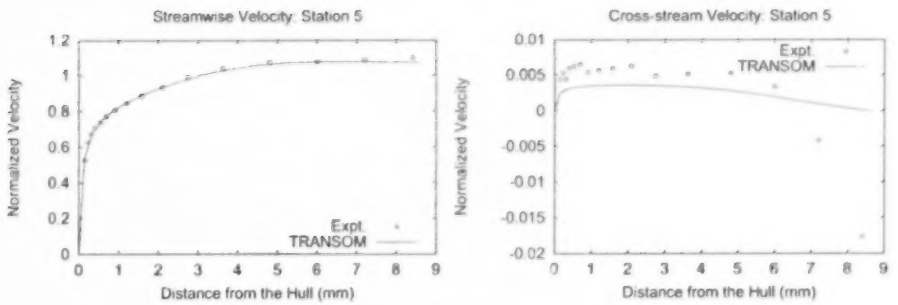

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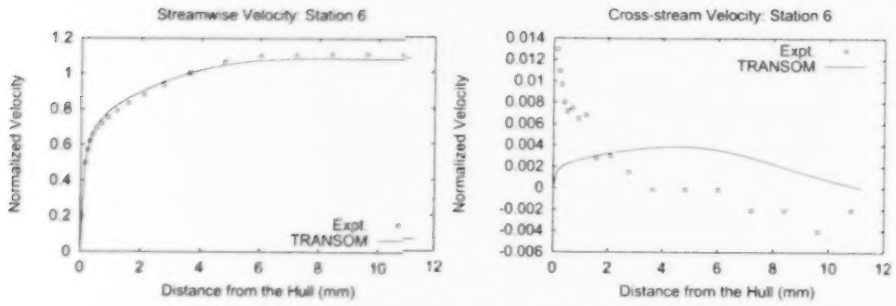

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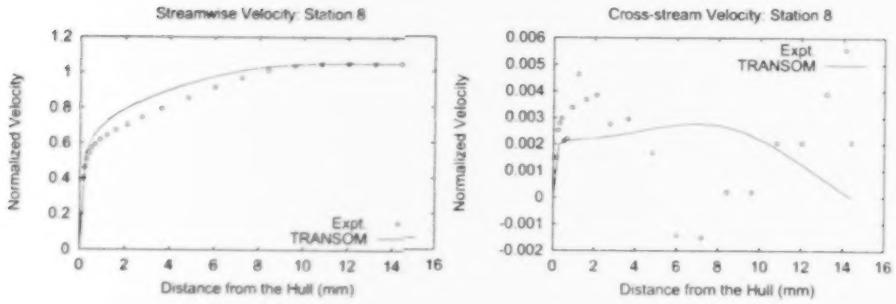

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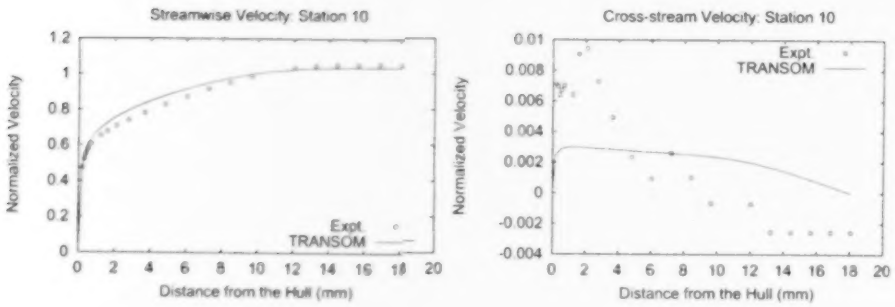

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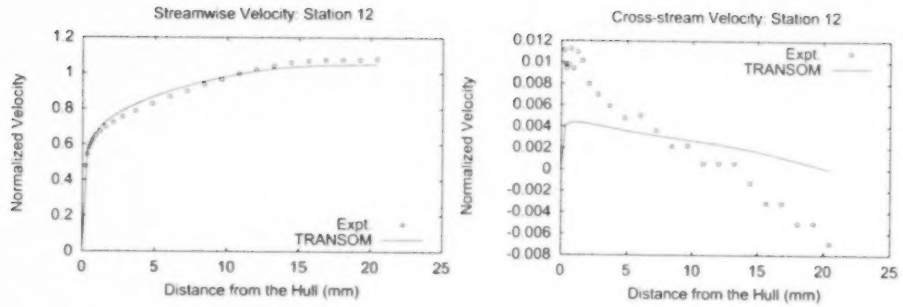

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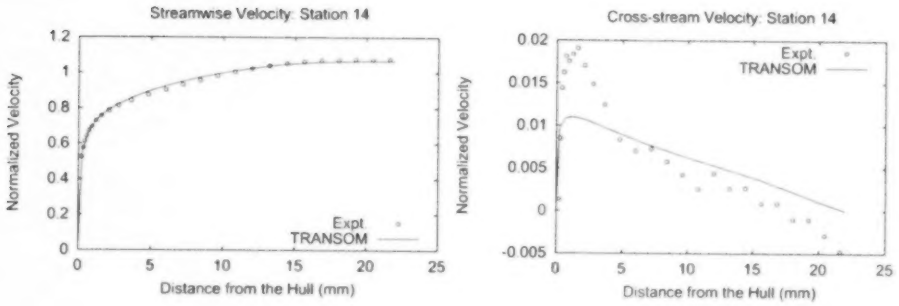

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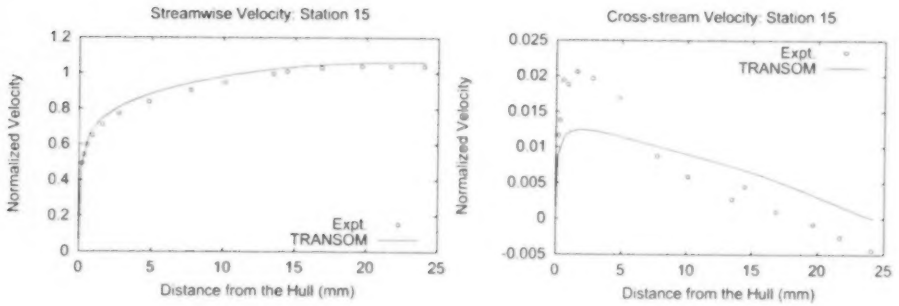

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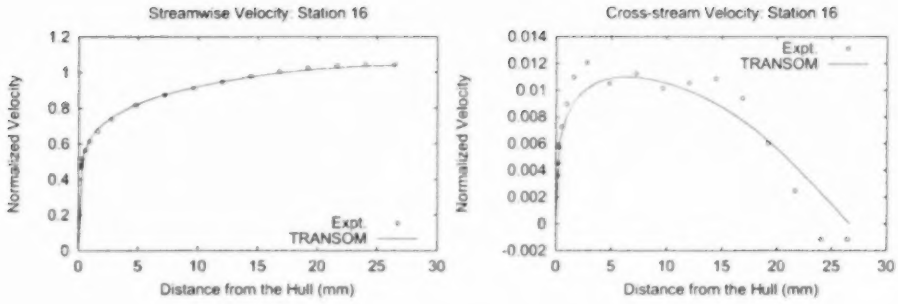

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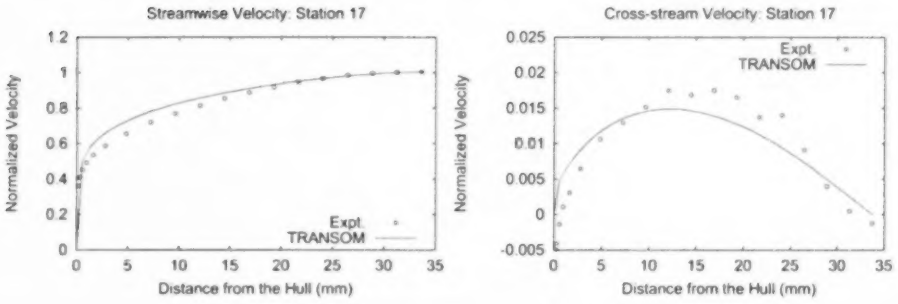

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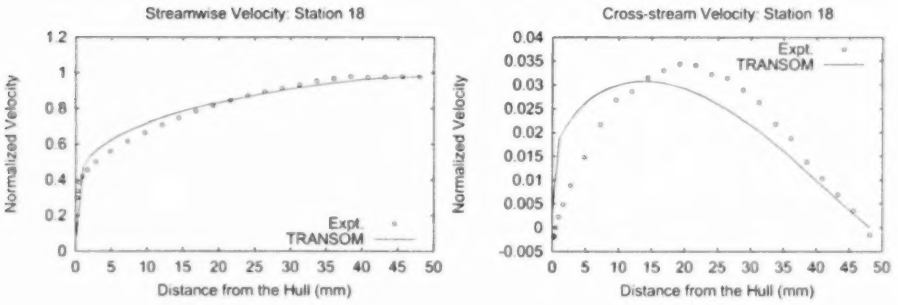

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β: Angle between the velocity and the potential flow velocity.

β_o: The angle between Larsson's calculated potential flow velocity and the measured velocity at the outermost point of a profile.

ν: Kinematic viscosity.

$\hat{\mathbf{n}}_c$: Unit vector in the cross-stream direction.

$\hat{\mathbf{n}}_s$: Unit vector in the streamwise direction.

$u_\star$: Friction velocity on the hull: $u_\star^2 = \tau$ where τ is the shear stress at the hull.

$\mathbf{V}_o$: Velocity vector at the outermost point on a profile.

V_x: Downstream velocity component.

V_y: Horizontal velocity component: i.e. the component normal to the centreplane.

V_z: Vertical velocity component.

y^+: Non-dimensional distance from the hull: $y^+ = u_\star y/\nu$, where y is the distance from the hull.

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The Reynolds-averaged Navier-Stokes solver TRANSOM, developed at Defence Research Establishment Atlantic (DREA), has been used to calculate the flow around the double hull ship tanker model SSPA~720. The Spalart-Allmaras turbulence model was used. The results have been compared with the hot wire anemometry data of Larsson. Agreement between the calculations and experimental data is very good suggesting that the Spalart-Allmaras model will be sufficient for calculating the flows around many of the hulls of interest to DREA.

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SSPA 720
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